Conventional Beams
Lecture I

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Neutrino Physics Summer School
Fermilab
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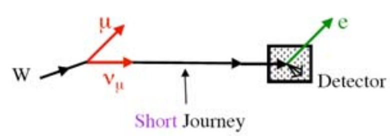
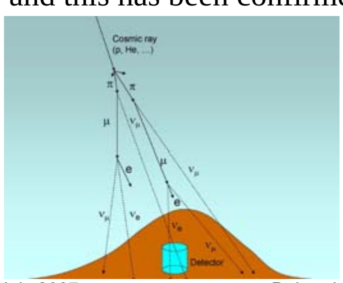
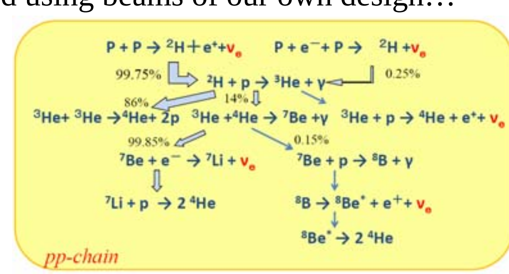
Putting this course in context

- Boris Kayser: Neutrinos change flavor over long journeys
  this has many ramifications
- Takaaki Kajita: using cheapest neutrino beams available, we have seen neutrinos "disappear" or change flavor, and this has been confirmed using beams of our own design…



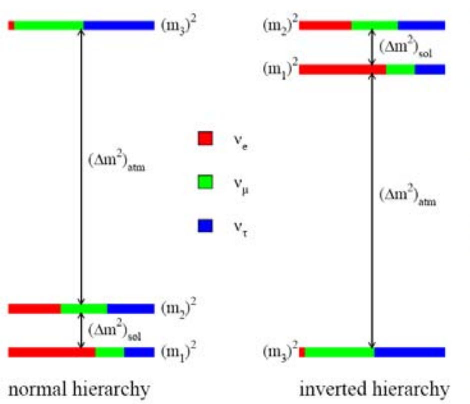
Is Not Seen But…





More Context

- Andre DeGouvea described the open questions



- What is the ν_e component of ν_3? ($\theta_{13} \neq 0$?)
- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi$?)
- Is ν_3 mostly ν_μ or ν_τ? ($\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4$?)
- What is the neutrino mass hierarchy? ($\Delta m^2_{13} > 0$?)

Still more context

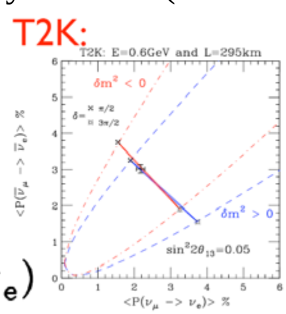
- Steve Parke told you about (theoretical) strategies:
  - From Probabilities to fundamental parameters
  - Need to measure

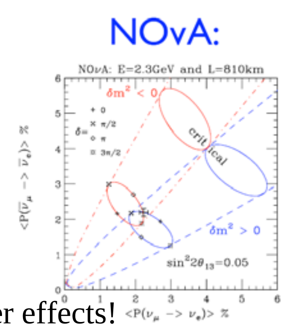
$$P(\nu_\mu -> \nu_e)$$

and

$$P(\overline{\nu}_\mu -> \overline{\nu}_e)$$

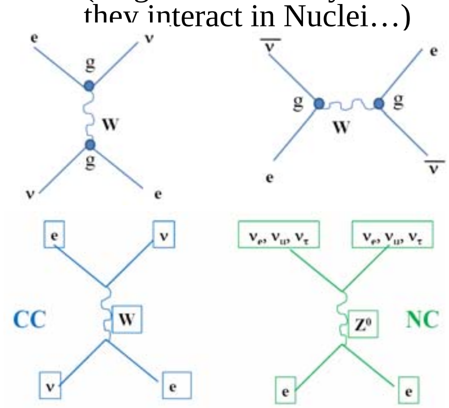
at more than one L and E, and need matter effects!

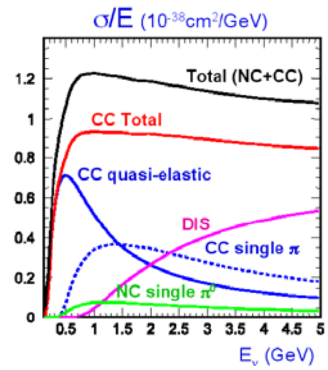




From Theory to Experiment

- Tsuyoshi Nakaya told you about how Neutrinos interact in Matter:
  - (Jorge Morfin told you how they interact in Nuclei…)

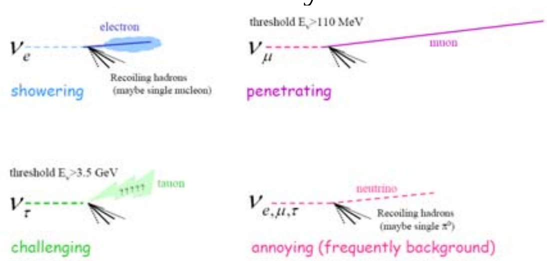


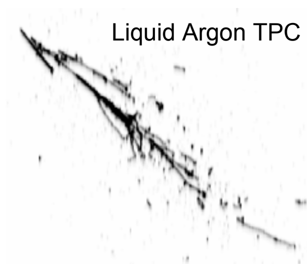


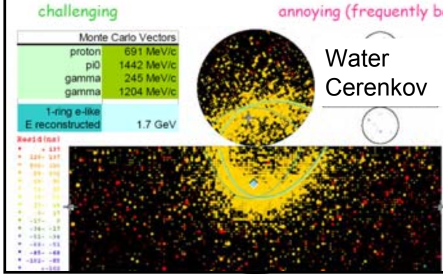
Measurement Picture not as clear (yet…)

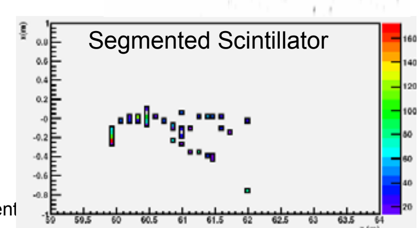
Seeing Neutrinos Interact

- Ed Kearns told you how to detect those interactions



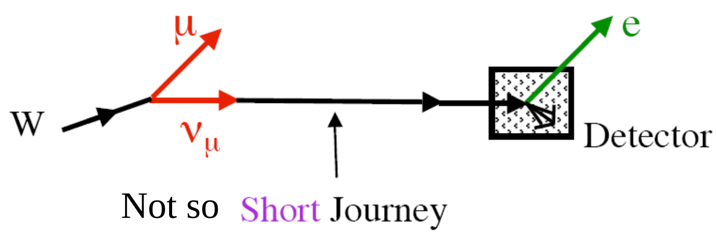






What is missing?

- How to design a Neutrino Beam: this is not the whole story:



- Getting from Numbers of Events in Detectors to Oscillation Probabilities (Lecture II)

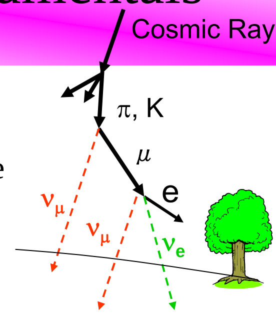
Outline for the rest of this talk

- To reach all of the goals we heard about from Andre, we will need several accelerator-based experiments….
- At this point, you could hear a sequence of mini-talks about the conventional beamlines for the following experiments:
  - K2K → Past
  - MINOS → Present
  - MiniBooNE → Present
  - OPERA → Present
  - T2K → Future
  - NOvA → Future

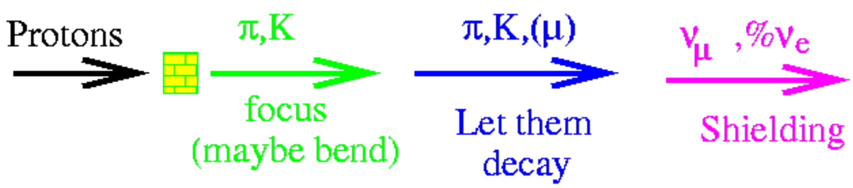
And I would have earned my trip to Batavia…but that's not the way I think about these experiments…so I'll talk about them all at once, step by step

Neutrino Beam Fundamentals

- Atmospheric Neutrino Beam (see Kajita's Lecture) :
  - High energy protons strike atmosphere
  - Pions and kaons are produced
  - Pions decay before they interact
  - Muons also decay



- Conventional Neutrino Beam: very similar!



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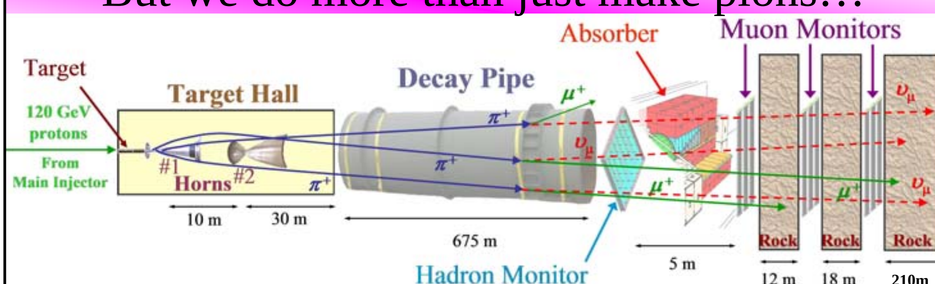
But we do more than just make pions…



Major Components:
- Proton Beam
- Pion Production Target
- Focusing System
- Decay Region
- Absorber
- Shielding…

Most ν_μ's from 2-body decays:

$\pi^+ \rightarrow \mu^+ \nu_\mu$
$K^+ \rightarrow \mu^+ \nu_\mu$

ν energy is only function of νπ angle and π energy

Most ν_e's from 3-body decays:

$\mu^+ \rightarrow e^+ \nu_e \nu_\mu$
$K^+ \rightarrow \pi^0 e^+ \nu_e$

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Proton Beam

- Rules of Thumb
  - number of pions produced is roughly a function of "proton power" (or total number of protons on target x proton energy)
  - The higher energy ν beam you want, the higher energy protons you need…

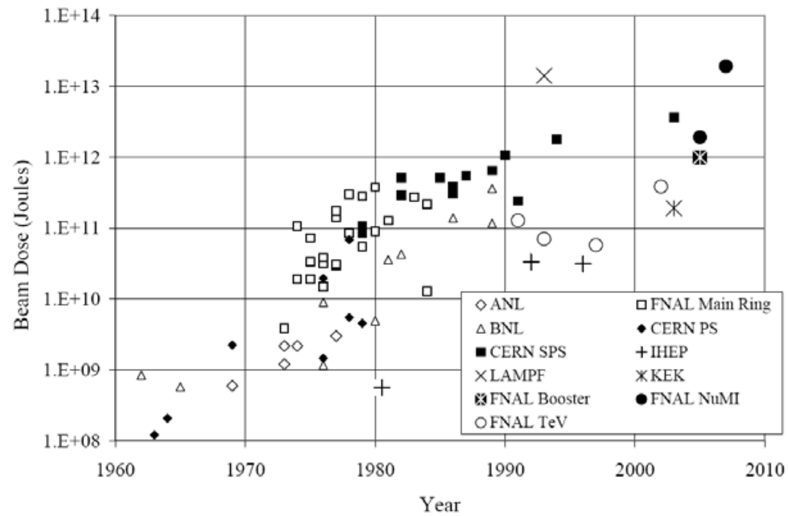
Proton Source	Experiment	Proton Energy (GeV)	p/yr	Power (MW)	Neutrino Energy (GeV)
KEK	K2K	12	$1\times10^{20}/4$	0.0052	1.4
FNAL Booster	MiniBooNE	8	5×10^{20}	0.05	1
FNAL Main Injector	MINOS and NOvA	120	2.5×10^{20}	0.25	3-17
CNGS	OPERA	400	0.45×10^{20}	0.12	25
J-PARC	T2K	40-50	11×10^{20}	0.75	0.77

Directing Protons is not trivial…

- Example from NuMI: extract beam from between two other beamlines, then make it point down at 3.5° so it comes through the earth in Soudan Minnestota, 735km away:

- Example from T2K: Proton source on prime real estate, direction to K2K determined, need to bend HE protons in small space: "combined function" magnets (D and Q)

Integrated proton power vs time…



- Reference: S.Kopp, Phys. Rep. 439:101-159, 2007

Neutrino Production Targets

- Have to balance many competing needs:
  - The longer the target, the higher the probability the protons will interact
  - The longer the target, the more the produced particles will scatter
  - The more the protons interact, the hotter the target will get—targeting above ~1MW not easy!
  - Rule of thumb: want target to be 3 times wider than +-1 sigma of proton beam size

	Target Material	Shape	Size (mm)	Length (cm)
Mini-BooNE	Be	cylinder	10	70
K2K	Al	cylinder	30	66
MINOS	graphite	ruler	6.4x20	90
NOvA	graphite	ruler	>6.4	90
CNGS	carbon	ruler	4mm wide	200
J-PARC	graphite	cylinder	12-15 mm	90

Target Photo Album

Question: Why this shape?

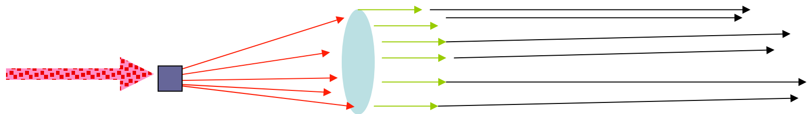
Shapes are similar, but cooling methods vary…some water cooled, some air cooled

Focusing Systems

- Want to focus as many particles as possible for highest neutrino flux
- Typical transverse momentum of secondaries: approximately Λ_{QCD}, or about 200MeV
- Minimize material in the way of the pions you've just produced
- What kinds of magnets are there?
  - Dipoles—no, they won't focus
  - Quadrupoles
    - done with High Energy neutrino beams
    - focus in vertical or horizontal, need pairs of them
    - they will focus negative and positive pions simultaneously

What focusing would work best?

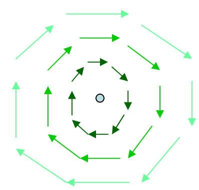
- Imagine particles flying out from a target:
  - When particle gets to front face of horn, it has transverse momentum proportional to radius at which it gets to horn



B Field from line source of current is

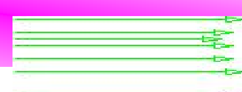
in the Φ direction

but has a size proportional to 1/r
(r=distance from current source)



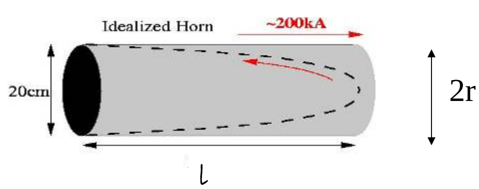
How do you get around this? (hint: $\partial pt \propto B \times \partial l$)

What should the B-Field be?

FROM  TO 

- Make the particles at high radius go through a field for longer than the particles at low radius. ($B \propto 1/r$, but make $dl \propto r^2$)
- Horn: a 2-layered sheet conductor
- No current inside inner conductor, no current outside outer conductor
- Between conductors, toroidal field proportional to 1/r

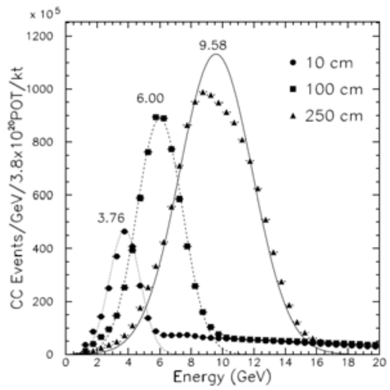
$$\delta p_t \approx \frac{e\mu_0 I}{2\pi cr} \times \frac{r^2 l}{r_{outer}^2} \approx \frac{e\mu_0 Il}{2\pi c} \times r \approx p_{tune}\,\theta$$



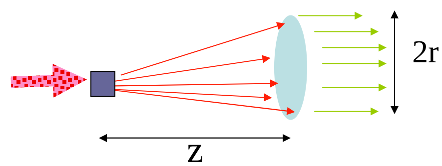
- There are also conical horns—what effect would conical horns have?

Tuning the Neutrino Beam Energy

- The farther upstream the target is, the higher momentum pions the horns can "perfectly focus"…see this by considering



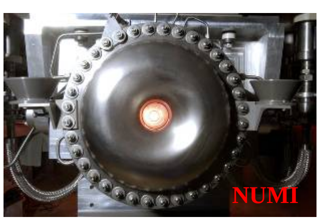
$$\delta p_t \approx \frac{e\mu_0 I}{2\pi c r} \times \frac{r^2 l}{r_{outer}^2} \approx p_{tune}\theta = p_{tune}\frac{r}{Z}$$

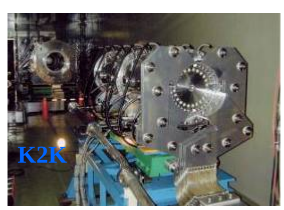


Reference: S.Kopp, Phys. Rep. 439:101-159, 2007

Horn Photo Album

	Length (m)	Diameter (m)	# in beam
K2K	2.4,2.7	0.6,1.5	2
MBooNE	~1.7	~0.5	1
NuMI	3,3	0.3,0.7	2
CNGS	**6.5m**	**0.7**	**2**
T2K	1.4,2,2.5	.47,.9,1.4	3





Horn World Record (so far): MiniBooNE horn pulsed for 100M pulses before failing

Horn Question:

- Given two horns that are each 3m long and 16cm diameter, what kind of current would you need to give a 200MeV kick to produced secondary particles?

$$dp_t(GeV) = 0.3B(T)l(m)$$

$$B(T) = \frac{\mu_0 I}{2\pi r} = 2\times10^{-7}\frac{I(Amps)}{r(m)}\left(\frac{r}{r_{\max}}\right)^2$$

$$I(Amps) = \frac{dp_t(GeV)}{0.3}\frac{2r_{\max}}{l}\frac{1}{2\times10^{-7}}$$

1) 2000 Amps 2) 20,000 Amps 3) 200,000 Amps

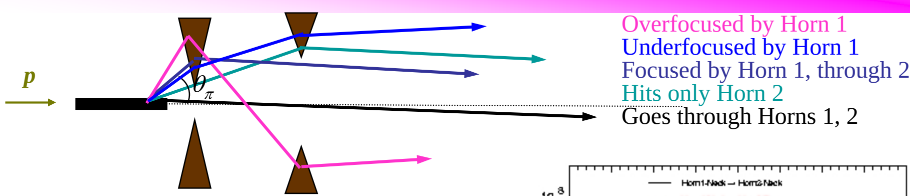
For pion going through "sweet spot", assume $r/r_{max}=1/2$

For MINOS, for example: (2 horns)

r=0.08m, l=3mx2: so for a 200MeV p_t kick, I=180kAmps!

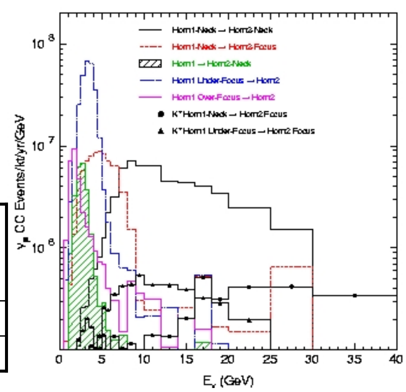
Designing what provides the 180kA is almost as important as designing the horn itself!

What happens if you have 2 Horns?



- Can predict components of spectra from apertures of horns.
- $\theta_\pi \sim p_T/p \; = r_{neck} \,/\, z_{horn}$.

	R_{neck} (cm)	Z_{horn} (meters)	Max pion momentum focused (GeV)	υ_μ Energy (GeV)
Horn 1	0.9	~1.0	~16	6
Horn 2	4.0	10	38	15



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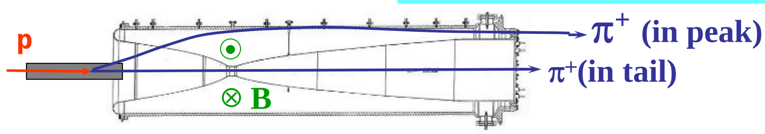
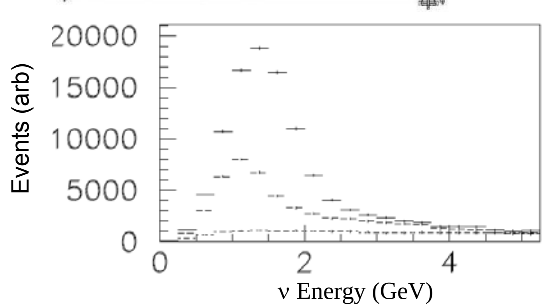
Besides target location, how else can you lower the neutrino energy?

- Reduce Current in the horns
  - That only helps a little…why?

$$\delta p_t \approx \frac{e\mu_0 I}{2\pi c r} \times \frac{r^2 l}{r_{outer}^2} \approx p_{tune}\theta = p_{tune}\frac{r}{Z}$$





MINOS Far Detector Spectra For 3 different Horn Currents

How do these pions (and Kaons) decay?

- In the center of mass of the pion: 2 body means isotropic decay, neutrino only has one energy
- Now boost to the lab frame: you can show (easily) that

$$E_\nu = E_\pi \frac{1 - \frac{m_\mu^2}{m_\pi^2}}{1 + \gamma^2\theta^2}$$

γ =boost of pion in lab
θ =angle between pion and ν

- And furthermore, you can show (slightly less easily) that the flux of neutrinos at a given location is simply

$$\Phi_\nu = BR \frac{1}{4\pi L^2}\left(\frac{2\gamma}{1+\gamma^2\theta^2}\right)^2$$

Thought question:
What about 3-body decays?
ν Energy
ν Flux versus Angle

Decay Regions

- How long a decay region you need (and how wide) depends on what the energy of the pions you're trying to focus.
- The longer the decay region, the more muon decays you'll get (per pion decay) and the larger ν_e contamination you'll have
- Again, tradeoffs between evacuating the decay volume and needing thicker vacuum windows to hold the vacuum versus filling the decay volume with Helium and thin windows, or with air and no windows…

	Length	Diameter
MBoone	50m	1.8m
K2K	200m	Up to 3m
MINOS	675m	2m
CNGS	1000m	2.45m
T2K	130m	Up to 5.4m

What is the ratio of ν_μ to ν_e in beam?

- Remember the Probability of π and μ decay

E=energy, t=lifetime, m=mass, g=Lorentz Boost of particle

$$\begin{aligned} P(\pi^+ \to \mu^+ \nu_\mu) &= 1 - e^{-\frac{t}{\gamma\tau_\pi}} \\ &= 1 - e^{-\frac{Lm_\pi c}{E_\pi \tau_\pi}} \\ P(\mu^+ \to e^+ \nu_e \overline{\nu}_\mu) &= 1 - e^{\frac{t'}{\gamma\tau_\mu}} \\ &= 1 - e^{-\frac{L' m_\mu c}{E_\mu \tau_\mu}} \\ &\approx \frac{L' m_\mu c}{E_\pi \tau_\mu}, \end{aligned}$$

L = decay pipe length

So what is L'?

"Decay pipe Length for Muons"

Beamline Decay Pipe Comparison

You can all show that neglecting things hitting the side of the decay pipe…

$$\frac{\Phi(\nu_e)}{\Phi(\nu_\mu)} = \frac{Lm_\mu c}{E_\pi \tau_\mu}\left(\frac{1}{e^{y_\pi}-1} + 1 - \frac{1}{y_\pi}\right)$$

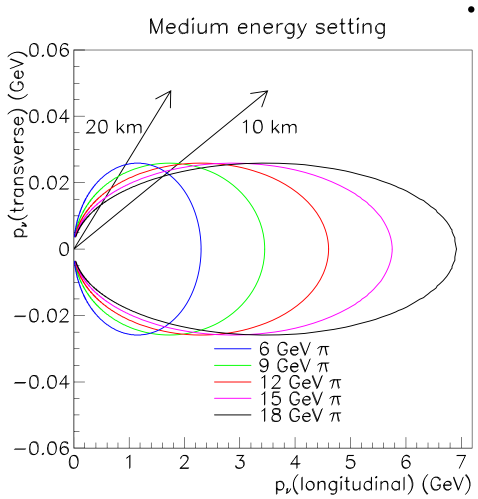
y_π=the number of pion lifetimes in one decay pipe… $y_\pi = \frac{Lm_\pi c^2}{E_\pi c \tau_\pi}$

	Length	E_π (GeV)	y_π	y_μ	$\Phi(\nu_e)/\Phi(\nu_\mu)$ (theoretical)
MiniBooNE	50m	2.5	0.36	0.3%	0.15%
K2K	200m	3.5	1.0	0.9%	0.5%
MINOS (Low Energy)	675m	9	1.3	1.2%	0.8%
MINOS (Med. Eng)	675m	15	0.78	0.7%	0.4%
CNGS	1000m	50	0.36	0.3%	0.15%
T2K	130m	9	0.47	0.2%	0.10%

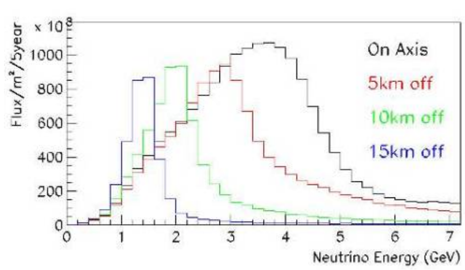
Decay Pipe Photo Album

Off Axis Strategy

$$E_\nu = E_\pi \frac{1 - \frac{m_\mu^2}{m_\pi^2}}{1 + \gamma^2\theta^2}$$



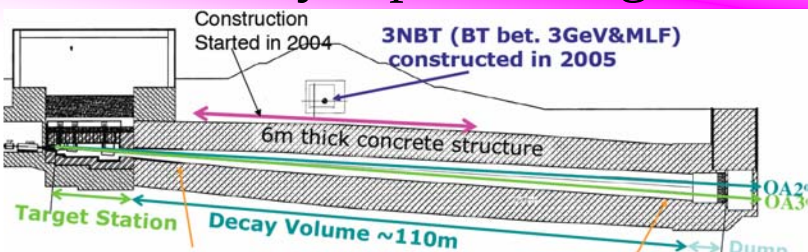
- Trick used by T2K, NOvA (first proposed by BNL)
  - Fewer total number of neutrino events
  - More at one narrow region of energy
  - For ν_μ to ν_e oscillation searches, backgrounds spread over broad energies



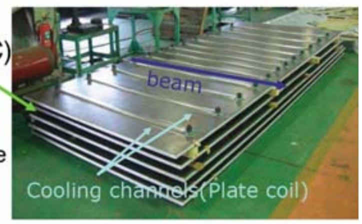
Only a consequence of 2-body decay!

Decay Pipe Cooling

Slide courtesy C.K.Jung



- Cover Off Axis angle : 2°~3°
- Square box shape made with water cooled iron plates (T<60°C)
- Filled by 1atm Helium gas
- Construction started
  - Crossing 50m part w/ 3NBT by June 15, 2005
- Remaining part in 2007&2008



Neutrino Beam Divergence

- For a perfectly focused monochromatic pion beam, how wide is the neutrino beam?

$$\Phi_\nu = BR\frac{1}{4\pi L^2}\left(\frac{2\gamma}{1+\gamma^2\theta^2}\right)^2$$

At what θ is Φ(θ)= Φ(0)/4?

$$\left(\frac{1}{1+\gamma^2\theta^2}\right)^2 = \frac{1}{4}$$

$$\theta = \frac{1}{\gamma}$$

Where is Φ(θ)= Φ(0)x0.99?

$$\left(\frac{1}{1+\gamma^2\theta^2}\right)^2 = 0.99$$

$$\theta = \frac{0.07}{\gamma}$$

Follow Up Question:

- How much additional divergence is added due to multiple scattering?

$$\vartheta_{rms} = \frac{13.6MeV}{\beta cp}\sqrt{\frac{x}{X_0}}$$

$$\vartheta_{rms} = \frac{0.1}{\gamma}\sqrt{\frac{x}{X_0}}$$

  - Filling the decay pipe with air?

    x=γcτ=γ(7.8m) X_0=304m

$$\vartheta_{rms} = \frac{0.1}{\gamma} * .16\sqrt{\gamma}$$

  - a 1mm Aluminum window?

    x=1mm X_0=89mm

$$\vartheta_{rms} = \frac{0.01}{\gamma}$$

Additional Question

- How does the loss of neutrinos from divergence compare to the loss of neutrinos due to pion interactions?

$$e^{-x/\lambda_{INT}} \approx 1 - \frac{x}{\lambda_{INT}}$$

- Filling the decay pipe with Air:

  x=γcτ=γ(7.8m) λ_{int}=692m/0.66 Lose 0.007γ

- 1mm Aluminum Window

  x=1mm λ_{int}=390mm/0.66 Lose 0.002

Decay Pipe Effect Summary

	Additional RMS (θ_{rms})	Flux Loss	Loss from Interactions
Filling with Air:	$0.016/\sqrt{\gamma}$	$.001\sqrt{\gamma}$	0.007γ
1mm Al Window:	$0.01/\gamma$	.0002	0.002
Where are they =?	γ=0.8	γ=0.8	γ=0.3

Remember, at an angle θ, flux is lower by

$$\left(\frac{1}{1+\gamma^2\theta^2}\right)^2$$

Moral of this story: Different p energies imply very different decay pipe choices

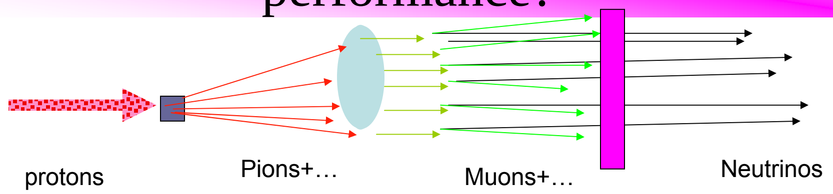
Caveat: all this is for perfectly focused beams…

	E_π (GeV)	γ_π (peak)	choice
MiniBooNE	2.5	18	air
K2K	3.5	26	He
MINOS	9	66	vacuum
CNGS	50	370	vacuum
T2K	9	67	He

Absorbing Hadrons

- As proton power gets higher and higher, have to think more and more about what will collect all the un-interacted protons!
- MINOS Absorber (1kton):
  - Water-cooled Al core
  - Surround with Steel
  - Surround with concrete
- CNGS Absorber
  - Graphite core + Al cooling modules
  - Surround with cast iron
  - Surrounded by rock
- Note: for 10^{20} protons on target per year, roughly 10^{19} per year hit the absorber…

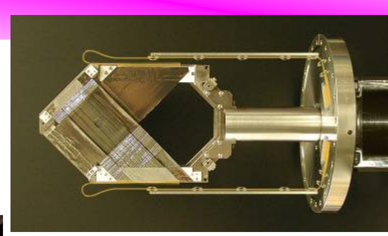
How can you measure the beam performance?

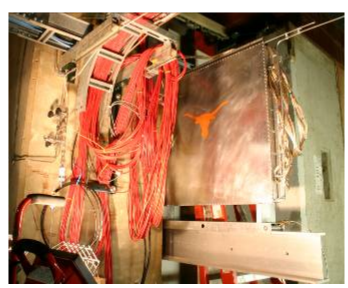


- Remnant Proton Measurements
  - Tales from the front line: NuMI and the target leak
- Muon Measurements
  - 7^{o} muon spectrometer (MiniBooNE)
  - "Range stack" Muon Monitor system (MINOS)

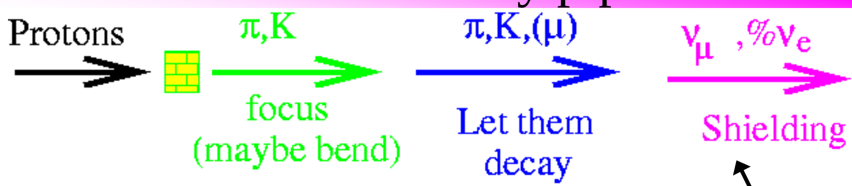
Neutrino Beamline Instrumentation

- Proton Beam
  - Number of Protons on Target
  - Position and angle
  - Spot size of beam on target
  - Proton Losses before target
- Target
  - Position and angle
  - Is it intact?
  - Temperature
- Horns
  - Position and angle
  - Current
  - Is it intact?
  - Temperature
- Absorber
  - Temperature

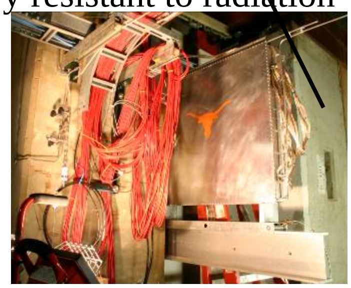




What about seeing the Protons at the end of the decay pipe?

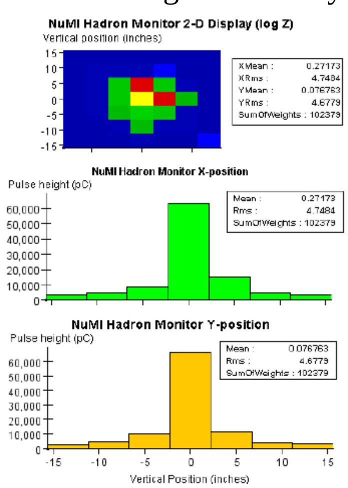


- Proton rates are now very intense: can use ionization chambers, but they must be very resistant to radiation damage, and can be low gain
- Question: what else makes it down to the end of the decay pipe?
  - Muons from pion decay
  - Undecayed pions
  - Secondary shower particles

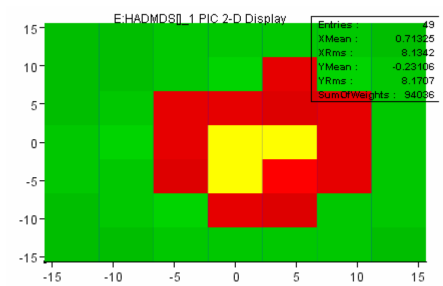


Seeing protons at end of pipe

No target in the way

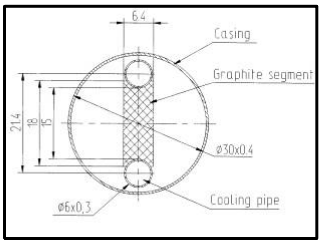


Target in the way

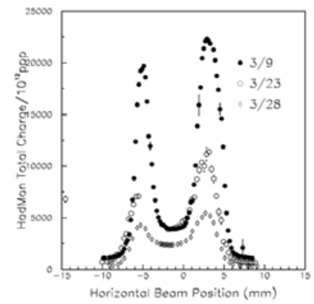


For most beamlines, this "hadron monitor" is really a proton monitor: it tells you about the protons and the target, but not about how well you are making neutrinos

Lesson Learned: be prepared for disasters…

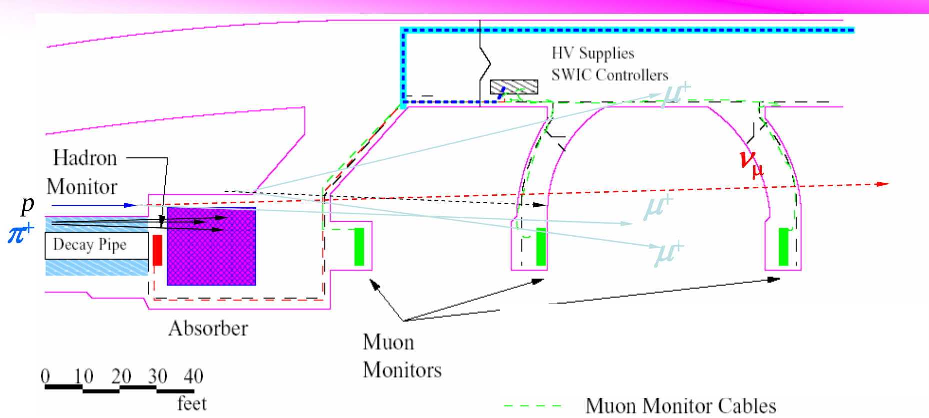


Look at what is between target and baffle by shooting protons there!



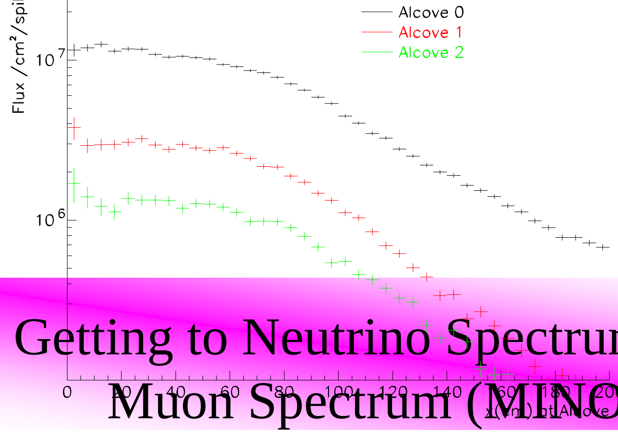
- Leaky Target at NuMI
  - the target has pipes around it that carry water to cool it
  - March 2005, discovered a leak: speculate the target surrounded by water…
  - Use Hadron Monitor to verify that water was there, and to check that it hasn't reappeared since we solved the problem…

Monitors to Study ν Beam (MINOS)

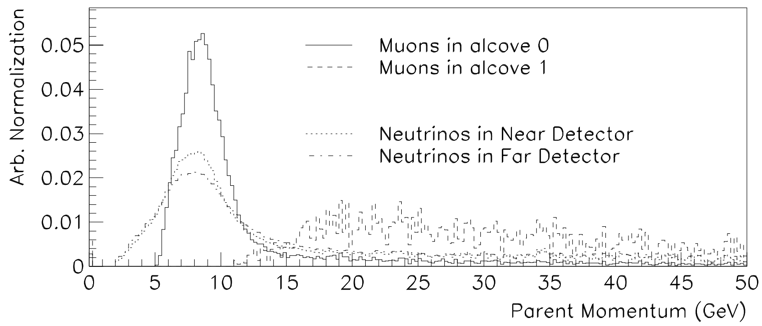


Hadron Monitor: sees uninteracted protons after decay pipe

Muon Monitors: 3 different depths means three different muon momentum spectra



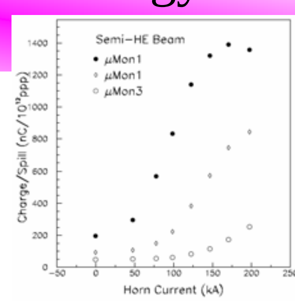
Getting to Neutrino Spectrum from Muon Spectrum (MINOS)

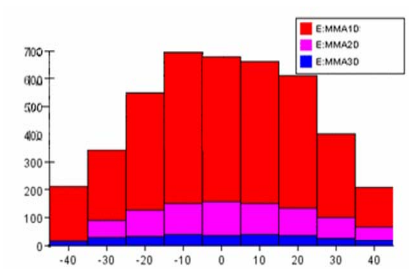


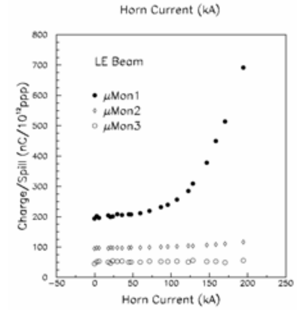
- As you get to higher muon energies, you are looking at higher pion energies…which in turn mean higher neutrino energies…

Muon Monitors in Different Energy Neutrino Beams

- By looking at the rates in the three different muon detectors, can see how the energy distributions of the muons changes
- Can study neutrino fluxes by moving the target and seeing how you make more high energy neutrinos the farther back you move the target
- Can study fluxes by changing the horn current and see how you make more low energy neutrinos as you increaste the horn current.



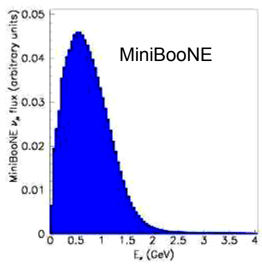


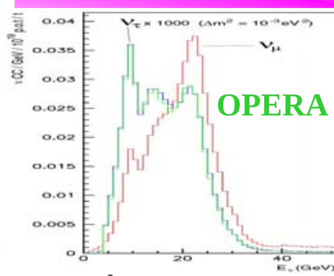


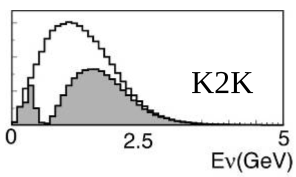
Graphs courtesy S. Kopp

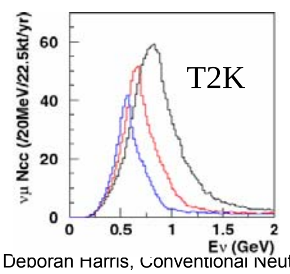
Oscillation Experiments: Beams past, present, and near future…

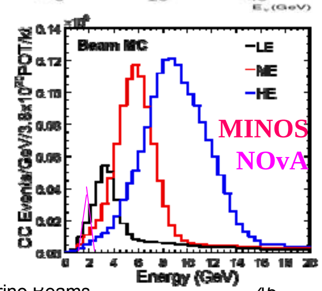
Exp’t	ν Energy (GeV)
MiniBooNE	1.2
K2K	1.4
MINOS	2-6
OPERA	15-25
T2K	0.7
NOvA	2



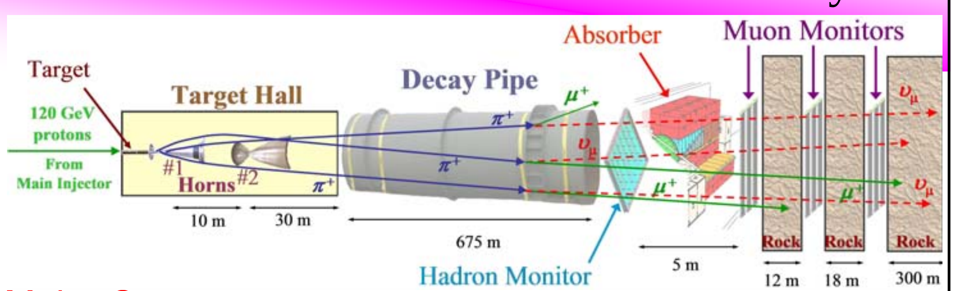








Conventional Neutrino Beam Summary



Major Components:

- •Proton Beam
- •Production Target
- •Focusing System
- •Decay Region
- •Shielding
- •Monitoring

Ways to Understand ν Flux:

Hadron Production

Proton Beam measurements

Pion Measurements

Muon Measurements

at angles vs momentum

at 0° versus shielding

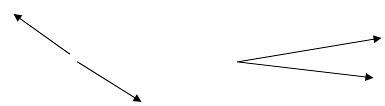
What else you can do with muons: Measure K/π ratio in Beam

- ν_e's from muon decay constrained by ν_μ spectrum (since they are part of the same channel)
- Kaons have no such constraint
- Remember problem set: to get the ν_e/ν_μ

Ratio you would also need to know the K/π production ratio (and focusing differences)

Any way this can be measured in the beam? Beam too hot to add Cerenkov counters to get track/track information

Think 2-body decay kinematics:

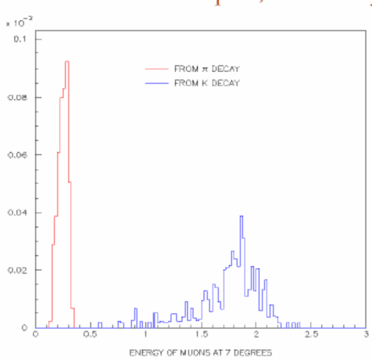


Center of Mass   Lab Frame

Decay	Maximum p_t
$\pi^+\rightarrow\mu^+\nu_\mu$	30MeV
$K^+ \rightarrow \mu^+\nu_\mu$	236MeV
$K_L\rightarrow \pi\mu\nu_\mu$	216MeV

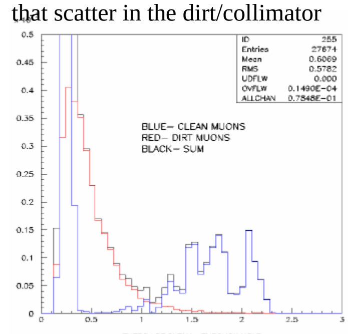
Example from MiniBooNE

Muons at 7° from pion, kaon decay:



- Clear separation between π and K decays.
- High apparent K/π parentage ratio:
  - most π in beam too high energy to produce 7° muon
  - Low-energy π more likely to have decayed upstream

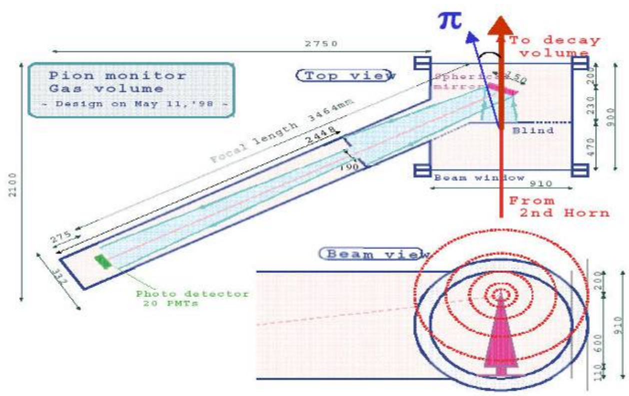
Backgrounds from muons that scatter in the dirt/collimator



- By adding collimator and spectrometer at 7°, they will measure
  - π/K ratio from difference in peaks
  - K/K_L ratio from μ^+ versus μ^-

Measuring π angular distribution in real beamline

- K2K Gas Cerenkov counter: measures angular distribution of Pions as function of momentum
- Located right after horns
- Works for pions above 2GeV



Measuring π angular distribution in real beamline